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Foundation Treatment of Embankment Dams With Combination of Consolidation and Compaction Groutings

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FOUNDATION TREATMENT OF EMBANKMENT DAMS WITH COMBINATION OF CONSOLIDATION AND COMPACTION GROUTINGS

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ABSTRACT

Treatment of soft or weak foundation in a rockfill dam is of importance due to being susceptible to the large settlements, which may cause the dam body subjected to undesirable deformations and even, catastrophic failures. In this paper the stress- strain behavior of an under construction 58 *m* embankment dam in North-West of Iran, namely Gerdebin dam, and its soft and weak alluvial thick foundation has been assessed numerically. The effect of combination of consolidation and compaction grouting of the basement (as a remediation method) on the dam deformations and stress levels, is investigated. For this purpose, a finite difference based software (FLAC 2D ver. 4.00) has been used to evaluate the effects of the governing mechanical parameters on the dam body behavior. Results show that for certain values of the mechanical properties of the grouted zone, the dam body deformations reaches to the minimum level. The mechanical properties of the grouted zone materials are dependent on the grouting pattern. Hence, an optimized grouting pattern has been achieved for such a case problem. Such an optimized grouting pattern is already under the executing procedure at the dam site.

INTRODUCTION

Treatment of soft or weak foundations in embankment and rockfill dams is of importance due to being susceptible to the large settlements, which may cause the dam body subjected to undesirable deformations and even, catastrophic failures. Depending to the type of foundation (rock or soil) the improvement methods might change. In case of alluvial foundations depending to the constitutive soil type methods like stone columns, jet grouting, deep mixing and compaction grouting might be used. In case of fine to medium fine heterogeneous soft soils it seems that the application of compaction grouting as a consolidation technique under the clay core could increase the stiffness of foundation in upper levels and reduce the risk of during operation settlements in dam body and foundations. Compaction grouting is a well-established mechanical in situ process that involves injection of stiff soil-cement grout under high pressure in order to displace nearby surrounding soil. Although due to low permeability of such soils the radius of influence of grouted zone might be limited; due to micro pile action of grouted zone the overall stiffness of the foundation will increase.

In this paper the stress- strain behavior of an under construction 58 *m* embankment dam in North-West of Iran, namely Gerdebin dam, and its soft and weak alluvial thick foundation has been assessed numerically from the mentioned point of view. For this purpose, finite difference based software has been used and sensitivity analysis has been performed on the elasticity modulus of the grouted zone to evaluate the effects of the governing mechanical parameters on the dam body behavior. This will result an applicable grouting pattern for reducing the settlements of foundation.

CASE STUDY DAM AND ITS FOUNDATION

Gerdebin Dam is a storage dam which is under construction in West Azerbaijan province in North-West of Iran, in 25km from Piranshahr city. This 48 *m* height dam is a zoned earth dam with vertical impervious clay core. The dam foundation generally consists of heterogeneous fine and coarse alluvial materials (with the thickness of 40 *m* below the maximum cross section) and followed by a week and crushed schist layer in depth (Fig.1). Regarding the unsuitable foundation situation and to reduce the dam body deformations, it is proposed to execute consolidation grouting beneath the clay core.
The mechanical properties of the dam body materials and its foundation are shown in Table 1, which have been taken from

the geotechnical site investigation and laboratory and in situ testing results. Also the typical cross section of the aforementioned dam is depicted in Fig.2.

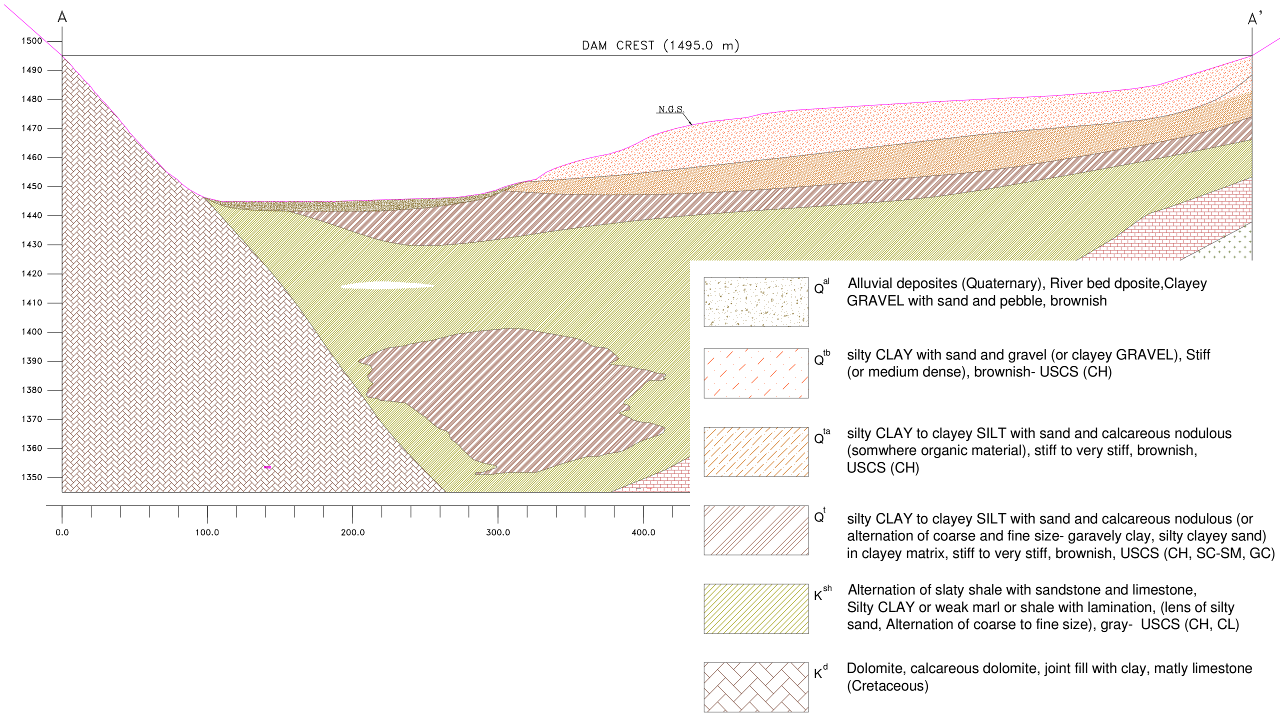

Fig. 1. Geotechnical profile of the natural ground along the dam axis

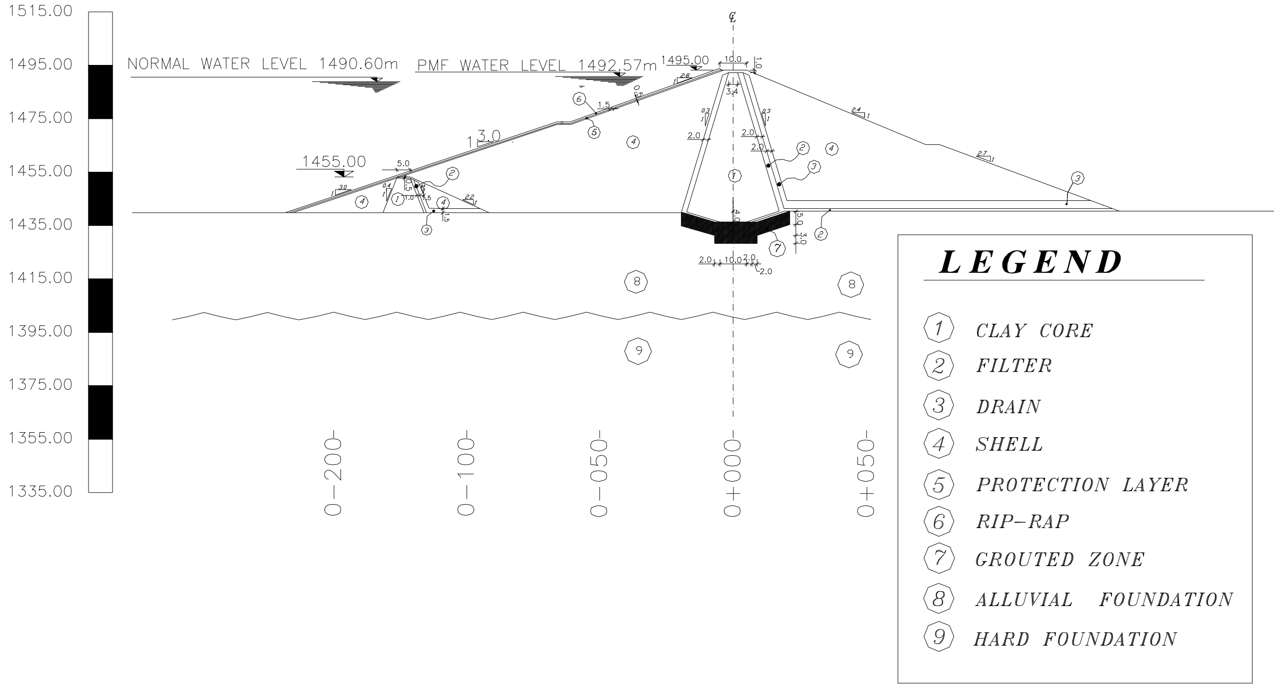

Fig. 2. Typical cross section of the Gerdebin dam

Table 1. Mechanical properties of the dam body and foundation materials of Gerdebin Dam

Material	Condition	Cohesion, c (kN/m^2)	Friction Angle, ϕ (deg)	Poisson's ratio, ν	Bulk density, γ (kN/m^3)	Modulus of Elasticity, E (kN/m^2)
Clay Core	Undrained	75	5	0.4	19	20000
Shell	Drained	4	37	0.3	25	40000
Filter & Drain	Drained	4	32	0.35	22	30000
Alluvial Foundation	Drained	50	27.5	0.38	19.5	18000
Schist Layer	Drained	110	31	0.45	25	1410000

NUMERICAL MODELING OF THE PROBLEM

To study the consolidation grouting role on improving the unsuitable dam foundation and its effect on the behavior of the Gerdebin dam, a finite difference based software, FLAC 2D; is selected and the dam body has been modeled during construction as well as its foundation. Also, sensitivity analysis has been performed on the stiffness properties of the grouted zone materials. It should be noted that staged construction modeling has been done based on Duncan (1992) suggestions.

An Introduction to FLAC 2D Software

As quoted directly from the software manual, FLAC is a two-dimensional explicit finite difference program for engineering mechanics computation. This program simulates the behavior of structures built of soil, rock or other materials that may undergo plastic flow when their yield limits are reached. Materials are represented by elements, or zones, which form a grid that is adjusted by the user to fit the shape of the object to be modeled. Each element behaves according to a prescribed linear or nonlinear stress/strain law in response to the applied forces or boundary restraints. The material can yield and flow and the grid can deform (in large-strain mode) and move with the material that is represented. The explicit, Lagrangian calculation scheme and the mixed-discretization zoning technique used in FLAC ensure that plastic collapse and flow are modeled very accurately. FLAC contains many special features including: Interface elements; Plane-strain, Plane-stress and Axisymmetric geometry modes; groundwater and consolidation (fully coupled) models; dynamic analysis capability; viscoelastic and viscoplastic (creep) models; optional two-phase flow model to simulate the flow of two immiscible fluids (e.g., water and gas) through a porous medium.

Modeling Assumptions

To model the dam body and its foundation the following assumptions have been taken into account based on literature suggestions such as Saboya and Byrne (1993) and Hunter (2003):

1- Dam body has been modeled in 17 layers regarding stage construction modeling;
2- During construction it has been assumed that the clay core has unconsolidated undrained behavior;
3- Clay core assumed to be unsaturated and going toward fully saturation on the foundation level at the end of construction;
4- Modulus of elasticity for the grouted zone materials has been assumed to change as 1 (namely no grouting), 5, 10, 50, 100, 500 and 1100 times of the elastic modulus of the alluvial foundation and, the maximum vertical deformations amidst of the dam body at the end of construction has been records to evaluate the most effective grouting pattern.

It should be noted that when the elastic modulus of the grouted zone materials is assumed to be equal to the modulus of the alluvial foundation, it means there is no grouting beneath the dam body and, when the elastic modulus of the grouted zone materials is assumed to be 1100 times of the alluvial foundation, it means there is a pure concrete zone (based on the modulus elasticity of the alluvial foundation and a concrete mass) beneath the dam body. Hence the sensitivity analysis has been performed between these two extreme conditions.

The modeled dam body geometry after construction is shown in Fig.3.

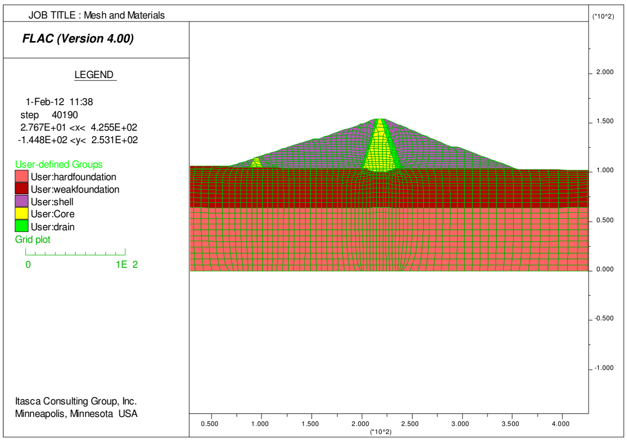

Fig. 3. Geometry of the modeled dam body and its foundation

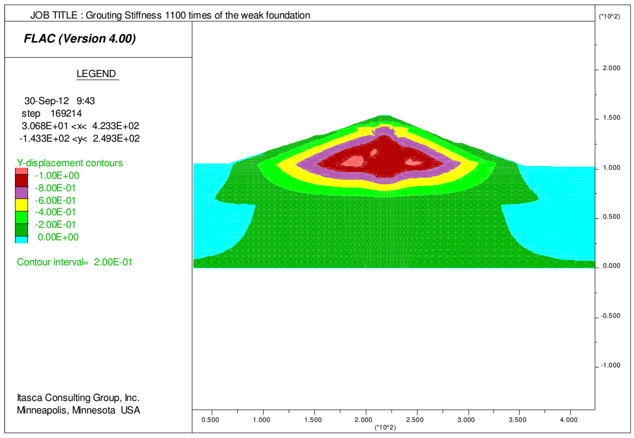

Fig. 5. Vertical deformations after construction for fully concreted grouting zone (m)

RESULTS OF NUMERICAL MODELING

Results of modeling show that consolidation grouting beneath the clay core has significant role on reduction of the dam body vertical deformations after construction as, it reaches from 128 *cm* for no grouting condition down to 99 *cm* for fully concreted grouting zone. Also, as expected, it has no role on lateral deformation of the dam body during construction. In Figs. 4 to 9, contours of vertical deformations, lateral deformations and vertical total stresses are depicted for two extreme cases (No grouting and fully concreted grouted zone).

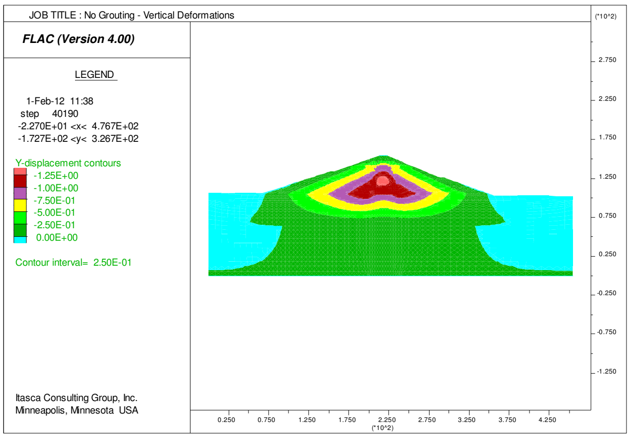

Fig. 4. Vertical deformations after construction for no grouting condition (m)

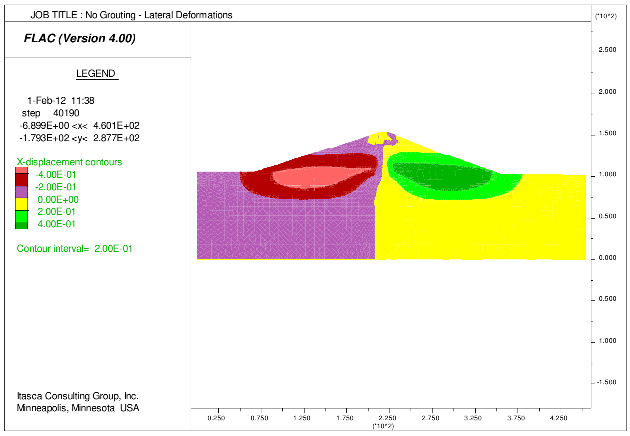

Fig. 6. Lateral deformations after construction for no grouting condition (m)

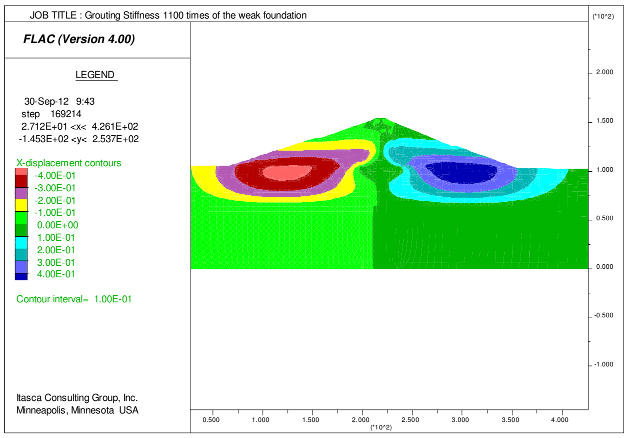

Fig. 7. Lateral deformations after construction for fully concreted grouting zone (m)

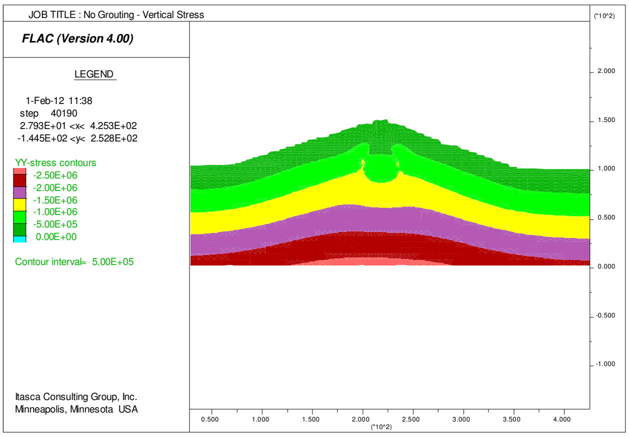

Fig. 8. Vertical total stresses after construction for no grouting condition (Pa)

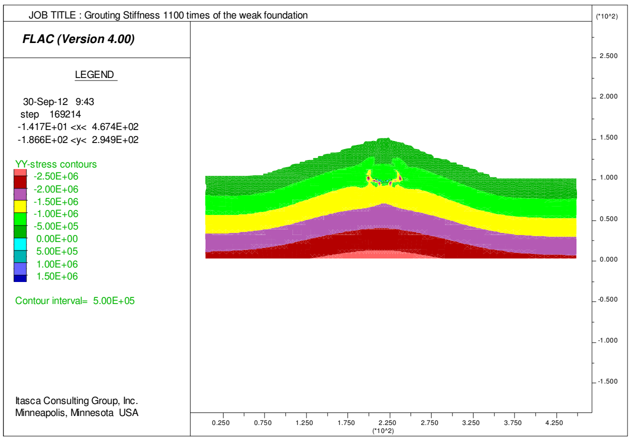

Fig. 9. Vertical total stresses after construction for fully concreted grouting zone (Pa)

By making comparison between Figs. 6 and 7, it has been revealed that lateral deformations after construction in not dependant on whether grouting executed or not and, its maximum value is about 0.4 m for these two cases. On the other hand, by comparing Figs. 4 and 5, it is obvious that the maximum vertical deformations shows reduction and also its form changes as, when there is no grouting it appears on the axis of the dam section while, for fully concreted grouting zone it moves toward the sides of the clay core. Also in Fig. 9, it is shown that stress concentration may occur in filter and draining materials near the foundation level when the grouting performed, due to stiffening the foundation beneath the clay core materials.

In Fig.10, the variation of vertical deformations inside the dam body is illustrated for other grouting stiffness conditions versus the dam elevation.

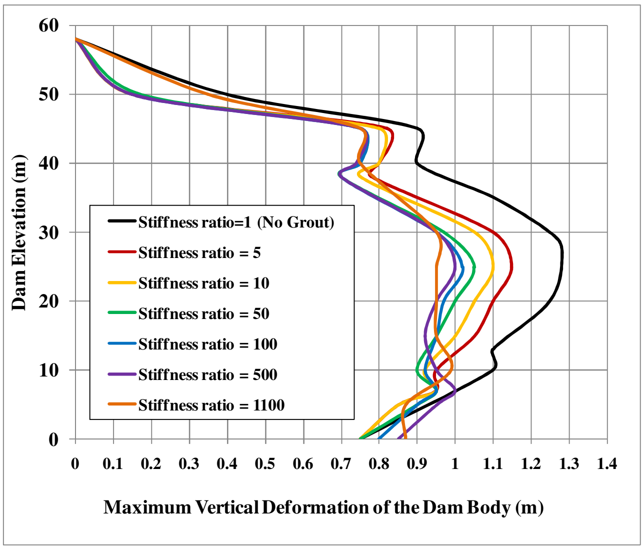

Fig. 10. Vertical deformations versus dam elevation for different grouting properties

As shown in Fig.10, it is concluded that all maximum vertical deformations occurs at the elevation of 25 *m* above the foundation.

In Fig.11 the variation of the maximum vertical deformations versus grouting stiffness ratio is shown, from which it could be concluded for the grouting ratio above 100, there is no considerable changing in maximum vertical deformations. Hence it appears that if the grouting procedure could increase the stiffness of the grouted zone materials up to 100 time of the alluvial foundation stiffness, it is optimally acceptable in both technical and economical points of views.

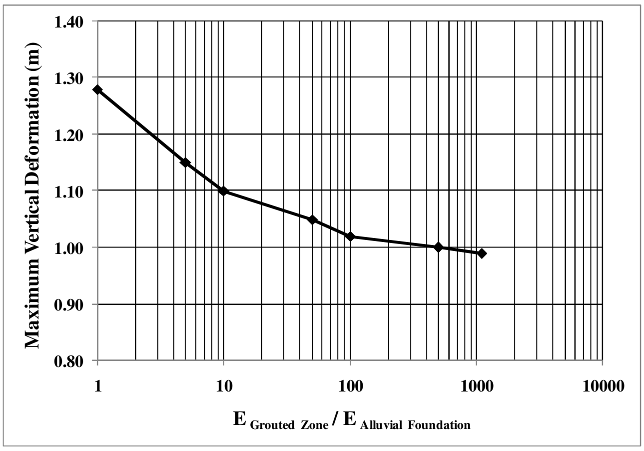

Fig. 11. Maximum vertical deformations versus different grouting ratios

TEST GROUTING BOREHOLES

To investigate the effects of grouting pattern on the grouted zone material stiffening, 5 numbers of grouting holes have been drilled with the depth of 8 meters and then injected by Portland cement mortars. The arrangement of the boreholes is depicted in Fig.12. First of all boreholes A and B were performed at the distances of 8m. Then borehole C has been drilled between these two boreholes and core samples obtained from the depth of 4m followed by fully injection of this hole. Then boreholes D and E were drilled and grouted in the same manners. The depths of all boreholes were 8 *m*.
It has been revealed that each borehole has an effective radius of 0.75 *m* around itself and the most effective arrangement achieved when the boreholes drilled in the distance of 2 *m*, center to center by each other.

On the other hand, from the core sampling it is concluded that average modulus of elasticity of the grouted zone materials could be presented as Table 2.

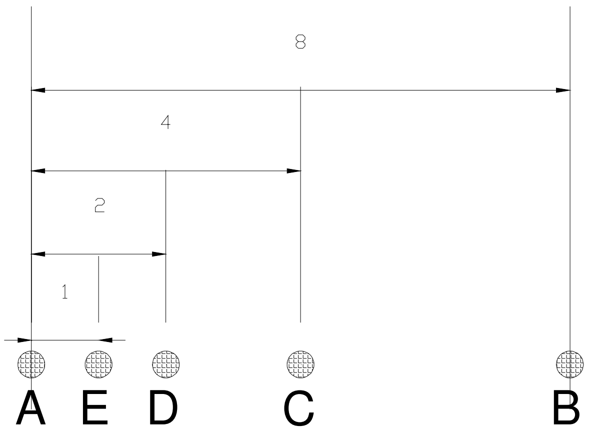

Fig. 12. Grouted boreholes arrangement (distances are in meter)

Table 2. Properties of the grouting zone materials

Borehole distance (*m*)	**Equivalent elasticity modulus of the grouted zone (*kPa*)**	$E_{grout}/E_{foundation}$
No grouting	18,000	1
8	145,294	8.1
4	479,017	26.6
2	**176,6979**	**98.2**
1	6,824,970	379.2

***Note*: All grouting boreholes are 8 *m* depth.**

Hence it has been concluded that grouting boreholes at the center to center distances of 2 *m* can improve the foundation properties and is the most economical choice of execution.
This pattern of injection is now under execution at the dam site. Figs.13 and 14 show a general view of the dam axis and preparation for grouting execution in excavated trench under clay core in right abutment.

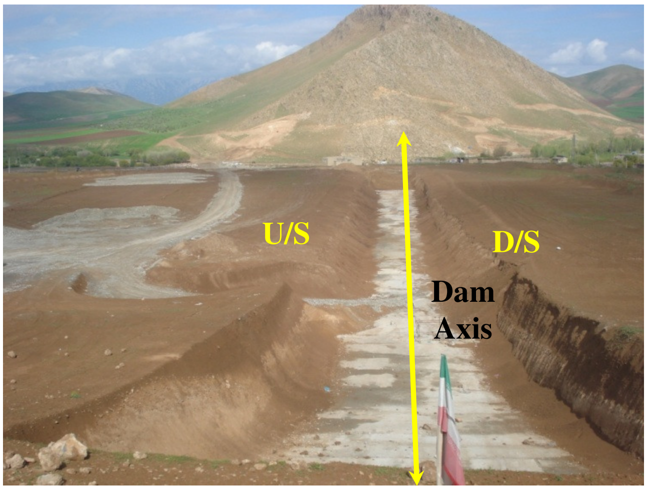

Fig. 13. A view from Gerdebin Dam Axis and preparation for grouting execution in excavated trench under clay core.

Fig. 14. Preparation for grouting execution in excavated trench under clay core in right abutment.

SUMMARY

In this paper a 48 *m* earth dam in Iran and its alluvial foundation has been modeled numerically by using FLAC 2D software and the effect of combination of consolidation and compaction grouting on its foundation treating has been investigated by performing sensitivity analysis of the grouted zone materials stiffness. The following results have been achieved through this study:

- This grouting can reduce the vertical deformations about 28% and has no effect on lateral deformations during dam construction.
- There is an optimum stiffness ratio about 100 times of the alluvial foundation stiffness at which the maximum vertical deformation reach to a reasonable value.
- By performing test grouting procedure it has been concluded that if the drilling boreholes have center to center distances of 2 *m*, the grouted zone stiffness reach to its desired value.

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